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THE CAPABILITIES OF A HYBRID HYDROFOIL SHIP IN RELATION TO OTHER SHIP TYPES

by

RICHARD THORNTON ROCKWELL

B.S., University of Washington

(1972)

Submitted in Partial Fulfillment of the
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June, 1979

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Submitted to the Department of Ocean Engineering on May 11, 1979 in partial fulfillment of the requirements for the degree of Ocean Engineer and the degree of Master of Science in Shipping and Shipbuilding Management.

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Thesis Supervisor: Philip Mandel
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CHAPTER I

INTRODUCTION

A. General Background:

Since the time of the Minoan fleets (3000-1450 B.C.), men have sought for some measure by which one ship design could be judged 'Better' than another. This thesis is yet another try at defining this measure, since in 4000 years no satisfactory one has been found. It is man's nature to compare and judge. Especially today when the United States Navy (herein referred to as the Navy) is trying to reconstruct its fleet with severely constrained resources.

The comparative measure should boil down to essentially a yardstick based upon value. Unfortunately, value is a slippery term. The value of an item implies a judgment call - a knot of speed may be worth more to one person than to another, similarly a Nautical Mile (Nm) of range, a ton of payload and many other parameters. Value per se, is not quantifiable today, hence it is largely ignored in favor of variables that are quantifiable.

The value of a warship has two facets. The first being its combat worth or capabilities for fulfilling its intended function. And secondly, value implies cost or how many resources are committed to producing the capability. Clearly, either facet may have a high value independent of the other. The ship designer's task is to raise the value of combat worth while holding the value of the cost to its lowest level.

Combat Worth is a term for a ship's capabilities in a combat environment, and not restricted to the scenarios envisioned by the designers or planners. But obviously some sort of scenario must be postulated to facilitate design decisions.

Since I am restricting this thesis to surface ships, a brief look at some surface warfare missions is appropriate. The greatest threat the Navy faces today, beyond local politics, is the growing Soviet Navy. Admiral Gorshkov (1) has written a book stating the goals and views of the Soviet Navy hence, in a sense, he has defined the current threat. His emphasis on submarines and our commitment to NATO adds credibility to the Anti-Submarine Warfare (ASW) mission. Convoys of raw materials to the United States and convoys of equipments to Europe add further justification. Since Admiral Gorshkov seems to place a great deal of importance upon coordinated operations of surface ships with submarines, the Anti-Surface Ship Warfare (SUW) mission and the Anti-Air Warfare (AAW) mission are also quite important.

Stryker (2) presents arguments for the importance/necessity of Sealift forces in both a peacetime and wartime condition. The massive amounts of material that must be transported must go by ship. These ships traverse Sea Lines of Communication (SLOC's). In a conflict situation these SLOC's are quite vulnerable to attack, hence, the ships that transit them must be guarded and protected. This protection operation encompasses all three mission areas -

ASW, AAW and SUW in what can be termed the Sea Control Mission.

Admiral Stansfield Turner has written that "...we must approach the use of the term 'Sea Control' from two directions; denying an enemy the right to use some seas at some times; and asserting our own right to use seas at some times." There is generally no argument with this statement. Although, Sea Control has been normally biased to emphasize the ASW mission, there are others (i.e. Keen (3)) who advocate a more balanced approach to Sea Control.

Keen is one among a growing number of advocates for the small fast ship. They see the Sea Control mission as more easily and cheaply performed by a collection of small fast ships. This thesis will limit discussion to this ship type.

When the subject of small fast ships is broached, interest normally is directed to the so-called unconventional, high performance or new technology ship types (Hydrofoils, Surface Effect Ships, Air Cushion Vehicles, Hybrids et al). There is good reason for this because certain aspects of their combat value are clearly superior to conventional ship designs. Unfortunately 'better' usually implies more costly. This is the crux of the comparative vehicle assessment problem.

Some critics seem to ignore the benefits of the Hi-performance vehicles entirely and base their arguments

upon other reasons. One of their reasons is the perceived lack of operational advantage in a tactical situation. This is reminiscent of the problems encountered by the Airships Akron and Macon (4) when they were introduced. Certain individuals can only envision a new concept as a direct replacement for an existing asset. Clearly this is facetious. New concepts require new tactics to exploit their advantages to the fullest.

Historically, innovative tactical employments have largely originated within the operating forces. Armchair and Computer analysis have contributed little to developing new tactical ideas, only refinements on old ideas. This is not to denigrate computer analysis. Rather, that the operating forces should be given their opportunity to work with these advanced vehicles to develop tactical employments that exploit their advantages to the fullest. You cannot learn to swim without getting wet.

Unfortunately another reason new concepts are opposed is because they are new. The following is a quote from Captain Thomas (5) which illustrates this point: "Navy historians recall that the change from sail to coal plodded a dreary path before verity vanquished vacillation. Coal was dirty, machinery unreliable, living conditions noisy, ships more expensive, overseas fueling stations unavailable, manpower requirements excessive, and the ponderous stacks - compared to the clean white sails of a four-masted man o' war -

most unesthetic. Many nautical puritans made their point well; and vocally if not logically delayed constructive progress. Fortunately the practical decisions of international neighbors induced the United Stated to furl its sails." This kind of thinking may be prevalent today.

There is a flip side to the preceding argument that also should not be ignored. Namely, new concepts should not be adopted just because they are new. 'Newness' is no guarantee of increased value, just look at your family car.

The sensible approach is embodied in the three criteria for Advanced Vehicle concepts as specified by the Navy's research and development program:

- It must be feasible
- It must be affordable and
- It must have military value.

If a vehicle meets these three criteria it may advance in the program to possible introduction to the fleet.

The first criterion, is usually easy to answer based upon engineering calculations. The second criterion is harder to answer in today's economy with any definitiveness. But it can be approximated closely. The last criterion is by far the most difficult. We will deal with it in this thesis in a simplifying way.

B. Basic Definitions:

A general breakdown of a warship is the following

adapted from Dr. Leopold (6). "The primary elements of a warship are 1) a platform to provide form and structure to contain and support all other components of the ship; 2) propulsion machinery for mobility; 3) a combat system consisting of weapons, sensors and data-handling devices to provide fighting capability; and 4) people to operate the ship."

This breakdown, although gross is suitable for comparative purposes.

1. The Platform Subsystem: The platform can take many forms in the way it performs the support and form functions. To illustrate, consider the four major new concept vehicles.

Hydrofoil Craft have a hull form that appears similar to a conventional displacement or planing hull. However, this shape supplies form and support only at rest or at low speeds. At higher speeds 'wings' supply the support to lift the hull clear of the water through the generation of hydrodynamic lift similar to the way an airplane's wing functions in air. The predominant advantage of this means of support is to decouple the hull from the motions of the sea interface. This leads to improved seakeeping and to the concomitant ability to achieve higher speeds in an adverse sea than the conventional monohull displacement form. Indeed, Klock (7) found that the Hydrofoil form was more 'efficient' than the rival monohull, air cushion vehicle or SWATH forms when employed in surface transport service in the North Sea area. This area is generally

considered to have the worst seas.

Air Cushion Vehicles (ACV) are becoming increasingly more common because of their amphibious capabilities. They are generally boxy in form and derive their support from an air bubble beneath the vehicle and contained by flexible skirts on all sides. They are also somewhat decoupled from motions of the interface which enhances their seakeeping and allows quite high speeds due to their low hydrodynamic resistance at these high speeds.

Surface Effect Ships (SES) are similar to ACV's with the exception of rigid side walls for the containment of their support bubble. They are therefore not amphibious but are capable of very high speeds with good seakeeping.

Small Water Area Twin Hull (SWATH) craft are entirely supported by buoyancy. They have very good seakeeping due to the minimization of their waterplane area. They are not suited for very high speeds but have exceptional stability.

Ships of the above types have been built in various sizes. They have been analyzed extensively and some could find wide acceptance in the future. See references (9) through (16) inclusive and current periodicals for further readings.

Hybrid Ship platforms, on the other hand, have not been built and are just now being analyzed to any extent. The following quote, from Dr. Leopold, will serve as an introduction to the Hybrid form.

'The idea of combining different hull supporting mechanisms in a single craft has led to the theoretical development of hybrid forms.

'One major advantage of these hybrid concepts is that they add variables so the designer can better accommodate to specific requirements and constraints. By the last decade of this century, technology will enable the production of such hybrids without significant problems.' (12)

To more easily understand the hybrid concept, the Sustention Triangle was developed to illustrate the various forms. (See Figure 1 on the next page.) This figure was developed by Jewell (17) as a method of categorizing vehicles by the identification of supporting forces or sustention. The method is convenient since it characterizes all vehicles by some combination of three forms of sustention.

- Unpowered Static Lift
- Powered Dynamic Lift
- Powered Static Lift

This can be presented in the form of an equilateral triangle with the three forms of sustention at the verticies as shown in Figure 1. This figure provides an insight into the nature of the current generation of high performance and hybrid vehicles, for they generally rely upon powered lift for their primary means of sustention. Hydrofoils are an example of the powered dynamic lift type vehicle and

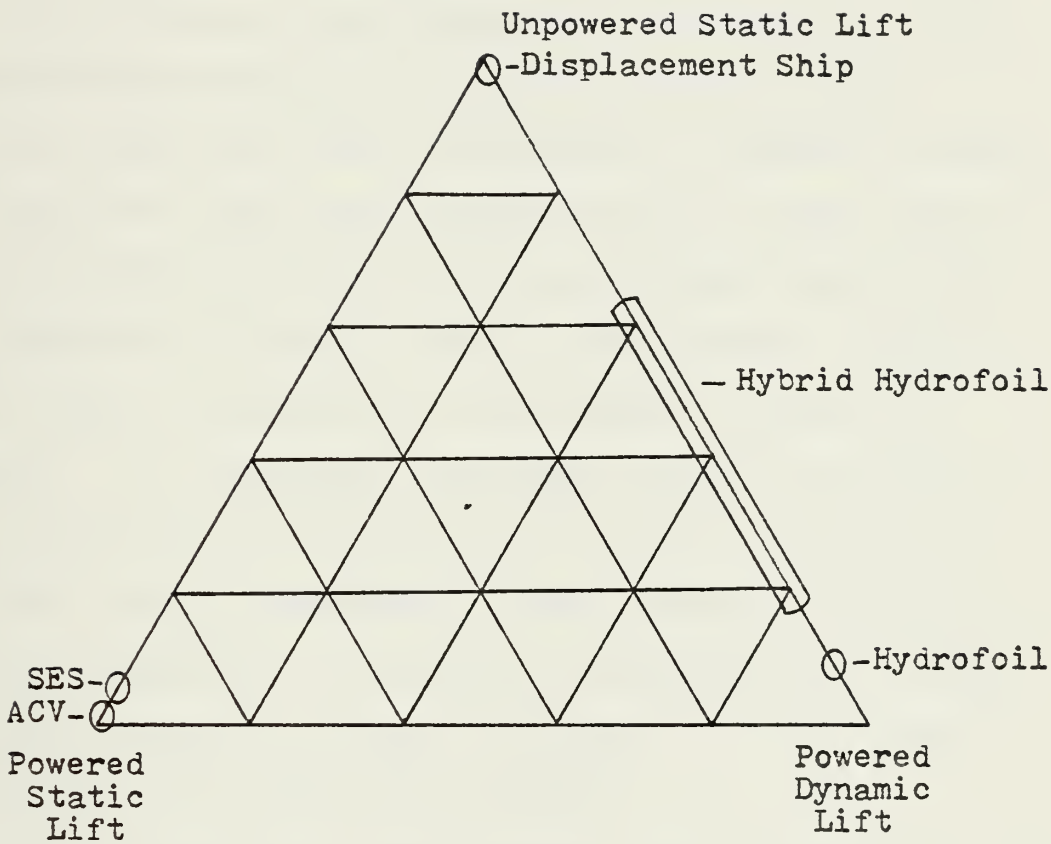

FIGURE 1   Sustention Triangle (17)

ACV's and SES's are examples of the powered static lift type vehicle. Unpowered static lift is characteristic of displacement and SWATH type vehicles. Planing craft generate dynamic lift forces at high speeds and are not solely static lift vehicles at high speed. Indeed, there is no such thing as a pure sustention mechanism. All of the previously mentioned craft derive parts of their sustention from more than one mechanism. Although in some cases these are very minor contributions, it does serve to illuminate the concept of hybrid craft types that derive their sustention from more than one mechanism. A hybrid vehicle may be classified to fall anywhere within the triangle. As is apparent, the hybrid craft is typified by a broad range of vehicles. The detailed analysis of this thesis will concentrate on only one hybrid concept - the Hybrid Hydrofoil. This type of vehicle falls on the Sustention Triangle as noted in Figure 1. It is termed a Large Hybrid Hydrofoil Ship (LAHHS).

2. Mobility Sybsystem: This second major element of a warship is typified by the power generation, transmission and application parts of the ship. There is little in this subsystem that is currently new in reference to advanced vehicles. Most employ gas turbines in various forms and lash-ups to provide propulsion and/or lift. There are radical new systems under development, such as super-conducting propulsion, but these systems are not now

employed in ship design and will not be discussed in this thesis.

3. Combat Subsystem: This represents the heart and soul of the warships capabilities. It is also probably the most difficult subsystem to deal with.

'Some of the most complex relationships evolve from the amount and type of payload to be carried by the ship. Payload includes armament, electronics. aircraft, ammunition, aviation fuel, and related spare parts and stores' (9). This is generally referred to as the Combat System of the ship. The following approach will be taken throughout this thesis.

First of all, Military Payload is defined as follows: MIL P/L (weight) = (Grp 4 (less 420,430) + Grp 7 + F20 (Ammo)). This is consistent with techniques employed at David W. Taylor Naval Ship Research and Development Center (DTNSRDC) (10).

Further, the term Combat Worth will be used to imply the combat capabilities of the ship. Combat Worth is based on two factors. The inherent capability of the design and the performance of the crew. Excellent crews can make a poor ship look good and conversely a poor crew can immobilize a good ship.

Crew performance is fixed at some level so that the only variable is the inherent capabilities of the ship system. Similarly, the level of technology employed in

the Combat System elements affects the capability. Again a fixed, arbitrary, consistent level of technology is assumed.

Therefore the parameter, Mil P/L, stands as a surrogate for portions of Combat Worth. This is patently false, but will allow some interesting insights as will be seen.

There are two more factors that enter the assessment of Combat Worth. That is vehicle Design Speed and Range. There have been innumerable articles and papers written about the value of speed over the past several years. The easiest way to treat this subject is to refer to Utility Theory. This theory leads us to believe that the first increase of a couple of knots in top speed at a low basis (say from 3 to 5 knots) will be worth more to us (have a higher utility) than a comparable increase of a couple of knots in top speed at a high basis (say 40 to 42 knots). This is generally evidenced in everyday life. The difficulty arises when we ask how much speed is enough.

The most suitable top speed is one that is called for by the combat environment. It is always advisable in combat to have the option to fight or run. This means to have the speed advantage over your opponent. Since our most likely opponent is the Soviet Navy, with an average fleet speed of approximately 35 knots, it would therefore seem advisable to design our combat ships with a minimum top speed of 40 knots. This allows us to have the fight/run option.

Many people have denigrated the value of speed in today's environment of supersonic missles and high speed torpedoes. It is well to remember that regardless of the speed of the weapons, the combatant vehicles must still come within range of one another. Having a speed advantage allows one to control the engagement by choosing whether to come within range or not.

As stated previously, I believe 40 knots to be the minimum speed that should be designed into Hybrid Hydrofoils. I do not advocate higher speeds unless they will provide a tactical advantage.

The Range factor is not as controversial as the Speed factor but it is of no less importance to the Combat Worth of the vessel. Range and Speed are intimately linked through the propulsion subsystem. High speeds require high power consequently large amounts of fuel.

Since ships of similar size and payload will be performing similar missions, their operating profiles are expected to be similar. This assumption allows us to evaluate the range factor at a fixed arbitrary Speed of Advance (SOA).

4. People Subsystem: The effect of the crew on the performance of the vehicle was stated above in section 3. In the following sections, complement levels are set at fixed levels corresponding to the size of the military payload as was done at DTNSRDC (10).

Finally, I would like to quote Kennell and Anderson (9). This "...study (is) influenced by a large number of variables. Some of these variables, such as (endurance speed), manning philosophy, maintenance philosophy and payload characteristics are operational 'requirements'. Others, such as habitability standards, margins, arrangements and subsystem types are design 'options'. Relationships between these variables must be established to assure consistent results in the study. Only in this way can the effects of variations in individual parameters be rationally examined. The validity of any parametric study is tied to this underlying web of inter-relationships."

To this end consistency of design was emphasized in this thesis. All designs (except as noted) were developed using the Hydrofoil Analysis and Design (HANDE) program resident at DTNSRDC, Appendix B. This allowed all designs to be based on the same philosophy and employ the same empirical relationships, thus aiding consistency and minimizing the variations in the inter-relationships.

CHAPTER II

COMPARATIVE VEHICLE ASSESSMENT

A. History

As mentioned previously, the comparative vehicle assessment problem has been around for thousands of years. Which I suppose is one measure of its difficulty. In all of this time, numerous techniques and measures have been formulated to facilitate the judgement of which ship is best. None have truly succeeded.

These measures have ranged from the simple one parameter 'mine is bigger' approach to the current multi-parameter, multi-index computer model. This logical progression from the simple to the more complex models has followed directly from the progression of man's abilities in the mathematical arts.

Since a warship is a highly complex, and sophisticated system, single parameter models have not worked. The multi-parameter models attempt to deal with the inherent complexity of the warship by introducing more and more measures. You soon reach a stage however, where you cannot even see the trees, let alone the forest, for all of the underbrush.

Another technique has been to deal with the performance of the warship in some specified environmental context. This scenario type evaluation comes closest to truly evaluating the ship performance. But it is easily misapplied.

B. Modeling Parameters

The following list of key modeling parameters are used in this thesis.

1. Weights / Weight fractions (W_x): These are listings of weights in various categories or as fractions of either full load displacement or light ship weight. The weight breakdown currently in use is that of the Navy's 'Ship Work Breakdown Structure' system classification (18). Weights will be presented in metric tons (Tonnes or MT).

2. Design Speed (V): This normally means the maximum speed the ship can reasonably attain. Design speed is a common key parameter. Design speed will be given in knots (kts).

3. Endurance Speed (Ve): It is sometimes called Range Speed and is normally that speed at which maximum range may be attained. In this thesis, range speed has a slightly different meaning. It is 35 kts, and fixed at this level somewhat arbitrarily whenever possible. This was done to enhance the comparability of different designs since it is difficult to judge the value of different ranges at different speeds. A fixed and relatively high speed of advance (SOA) was deemed to be more realistic than a maximum range at some design dependent speed. Endurance speeds will be given in knots (kts).

4. Range (2R): The range is that distance in Nautical miles (Nm) that the ship can traverse at the endurance

speed, starting with a normal full load of fuel. Operating Range (R) is the radius of a circular operating area equal to one-half of the Range.

5. Seakeeping: This is not a single parameter but rather a collection of diverse parameters. Since all of the designs analyzed in this thesis were designed to the same seakeeping standards; this mode of behavior will not be analyzed. When diverse ship types are compared, it is of paramount importance to include this behavior.

6. Military Payload (Mil P/L, Mp): This was previously defined but is repeated here for completeness: $M_p = (W_{400} - W_{420} - W_{430} + W_{700} + F_{20})$.

7. Combat Worth: In this thesis, Combat Worth will be defined as a combination of Military Payload, Design Speed and Range since these are felt to be the key elements in warship performance. More will be presented on this subject in Section E following.

8. Installed Power (Pi): The total installed (foilborne in the case of hydrofoils) propulsion power in metric horsepower.

9. Fuel Weight (M_F): This term is self-explanatory and is given in metric tonnes.

10. Crew Size (Nc): This term is also self-explanatory and is given as (number of officer/number of chief petty officers/number of enlisted) and the total complement. Crew size, in the designs later on, was taken as fixed for a fixed level of military payload as is done at DTNSRDC (10).

11. Price ($): The Price is a particularly political parameter but is absolutely required for a meaningful comparison. In this thesis, the Price will be defined as the contract price for the lead ship of a class expressed in fiscal year 1977 dollars. More on this in Section E following.

12. Intangibles: These are various attributes of a ship design that are not directly related to the performance of its mission. But they are none the less important to a fully functioning warship. Some of them, like Reliability, Maintainability, Availability (RMA), and Habitability are quantifiable to a certain degree. Others, such as operability, are not quantifiable at this time. In either case, their impact on Combat Worth, while inarguably important, is not easily measurable.

C. Techniques of Comparison:

Just as there are many parameters, so there are many comparison techniques. Almost all techniques focus their attention on selected subsets of the available parameters in order to make their point, since handling all of the parameters simultaneously is prohibitive.

One prevalent technique is called Ratio Analysis. This approach looks at weight fractions, volume fractions, etc., in order to lay bare the underlying differences between different designs. A good example of this technique in use is given in Graham, et al (16).

The technique of Ratio Analysis is admirably suited for comparisons of essentially similar designs such as the FF1037 Bronstein class vs. the FF1052 Knox class ships. This view is based on the facts that this technique rarely includes cost information directly and emphasizes engineering differences rather than performance differences.

Another technique that has been employed is the cost comparison approach. This technique attempts to define system costs so that judgments can be made between systems. This technique is typified by Femenia (19). This approach is fraught with political difficulties, but is employed by the civilian ship design sector with its emphasis on return on investment. Utilizing this technique in the military/governmental ship design sector is difficult due to the sensitive nature of costing and funding.

An adaptation of the cost comparison methodology that is employed in the government sector is one called Cost-Benefit Analysis. Unfortunately it currently has a poor reputation due to various manipulations in the past. Nevertheless, the underlying idea of including both cost (input) and benefits (output) is valid and will be employed in this thesis.

Another technique employed today is Scenario Analysis. Here the design is maneuvered through a carefully constructed mission scenario in order to evaluate its performance. This is normally accomplished with a computer

model, but the results are very sensitive to the input parameters defining the environment. A discussion on scenario dependence and cost/benefit analysis can be found in O'Neil (14).

The final technique I will mention is one I term Parametric Analysis. This approach utilizes various combinatorial parameters to compare designs. This is a very general approach with results ranging from very poor to very good. A good example of this technique in use is found in Rainey (15). I will use certain combinatorial parameters in the comparisons in Chapter III.

D. Comparative Pitfalls:

It is well to be aware of the numerous pitfalls to be avoided in the comparison process.

The first of these is the use of the terms 'better/best'. We undertake comparative analyses in order to find the 'best' ship designs. There are no 'best' designs. There are vessels that are 'better' than other vessels in a given circumstance, but there are no overall 'best' vessels. For example, consider the plot shown in Figure 2A on the next page.

The plot in Figure 2A is fictitious and is presented for illustrative purposes only. You will note that there is no overall 'best' design. There are local optimums wherein certain vessels are better than others within a given speed range. The circumstances of the comparison

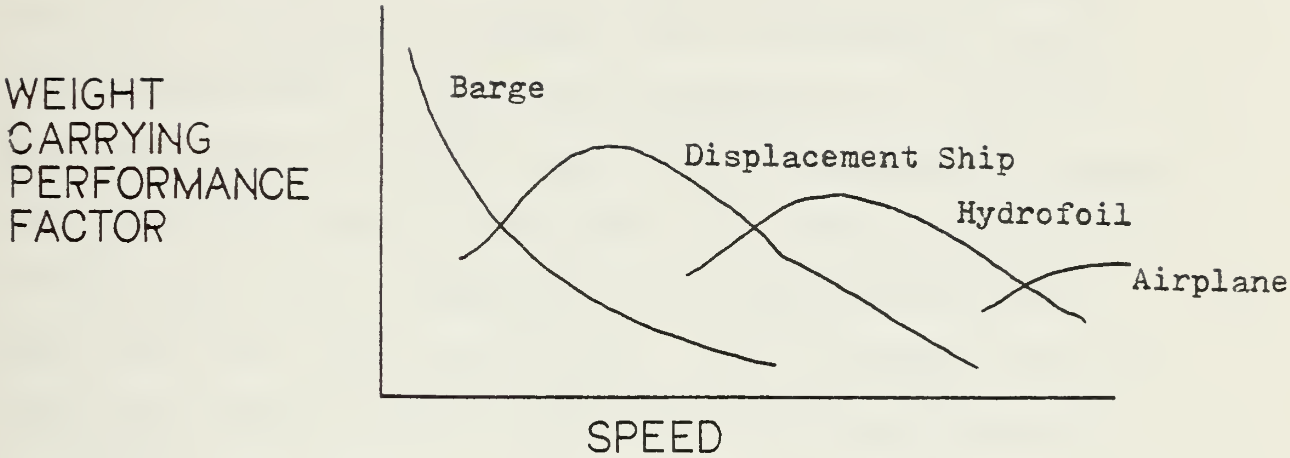

FIGURE 2-A

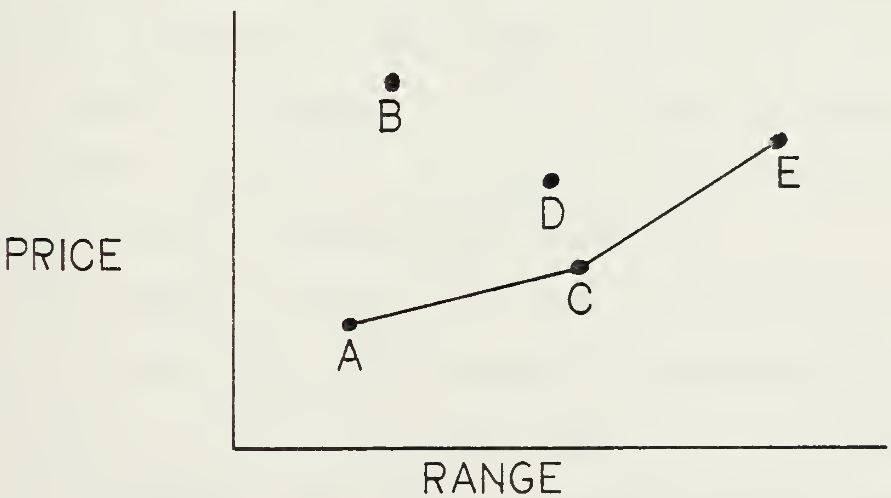

FIGURE 2-B Illustrative Comparison Curves

contribute to the selection of the 'better' design.

This leads to a related pitfall specific to scenario analysis. In scenario analysis, the circumstances can be easily manipulated. Since the circumstances can influence the evaluation, the utmost care must be exercised to evaluate the outputs in terms of the inputs. An example of this is the NATO short war or lightning war scenario wherein the entire Navy has very little value. And it follows that any particular design analyzed under these circumstances will have very little value. It is generally conceded that the NATO short war scenario has a very low probability of occurrence. This points up the important fact that the circumstances in the scenario must be true reflections of reality in order to arrive at meaningful results.

Yet another pitfall is the evaluation of intangibles. For example, the operability of vessels is not currently quantifiable. Operability does impact the worth of the vessel but cannot be analyzed, so it is normally neglected. These intangibles should be fed back into the results of the comparison prior to making any judgments.

The last obvious pitfall is a lack of consistency. By this it is meant that ship designs are compared that were not designed from a consistent data base. Different underlying assumptions can alter the designs hence altering the resultant comparisons.

E. Comparative Approach Utilized:

The comparison technique used in this thesis is a visual parametric one. This means that various parameters were plotted against each other in order to elicit visual evidence of inter-relationships and trends in performance.

The underlying assumption in this comparison technique is that the ship design is viewed as a Transfer Function. That is, that resources (inputs) are operated upon by the ship design Transfer Function to yield some amount of Combat Worth (output).

Analyzing the mechanics of Transfer Functions in isolation does not yield good results. Meaning, that analyzing the way the ship design converts money into Combat Worth is not necessary. Rather the behavior of the Transfer Function is what is important. Whether a Transfer Function places greater weight on one factor or another is not directly relevant. Whereas broad spectrum behavior pertaining to total ship system comparisons is relevant. This broad spectrum behavior is used to look at results (Combat Worth) versus resource commitment (Price).

One way to look at the results versus commitments is to refer to a trade-off boundary. This is illustrated in Figure 2B. (Again this is a fictitious plot used for illustration only.) The five point designs A through E represent equivalent ship designs in all factors except range. Designs A, C and E define a trade-off boundary in

that they define a 'most efficient' curve. As more and more range is required in the design, we traverse from A to C to E. Designs B and D are neglected because they are less efficient - i.e., it costs more to get the same range or conversely you get less range for the same price.

One of the difficulties with the Transfer Function technique is the selection of appropriate parameters for both input and output measures.

The price that would be contracted for by the Navy in executing a particular design was selected as an appropriate measure of the amount of resources committed towards achieving a given result from that design. Since actual cost data is not available for Hybrid ships (owing to the fact that none have yet been built), Cost Estimating Routines (CER's) were adapted from Reference (12) and are explained in Appendix A.

The Price figure that results from the application of the CER's, is for the projected contract price of the first of a class of vessels. The absolute magnitude of the Price figures appears to be overly pessimistic but are believed to be quite adequate for relative cost purposes.

Due to the scarcity of returned cost data on conventional combatant hydrofoils, the CER's were also employed to price out the conventional hydrofoil designs. This also ensures that costing is consistent throughout the comparison and allows judgments to be made on a relative cost basis.

The output of the Transfer Function in this thesis is not measured by a single parameter but rather by a group of parameters that must be treated together to represent Combat Worth. Military payload (Mil P/L) as previously defined, Range and Design speed, all taken together in various forms, are used to represent Combat Worth.

Speed was essentially held constant at about 40 knots (except as noted later) to minimize its effects leaving only Mil P/L and Range as variables. Mil P/L was set at four discrete values and Range allowed to be a dependent variable. Hence, within any payload grouping, all ships have the same speed and payload and the one with the greater range should have the greater Combat Worth. This is the approach utilized in Mandel (13).

The preceding is true up to a point. As Utility Theory shows, a fixed increase of any item has less and less value as the basis amount is increased. For example, we would probably not be willing to pay to increase the range from 90,000 to 100,000 miles, whereas we would certainly be willing to pay for an increase from 0 to 10,000 miles. However, the Range parameter is an acceptable measure within the limits observed in this thesis.

One other parameter was varied in order to evaluate its impact on the Transfer Function. This parameter was foil loading, a critical parameter in hydrofoil design, since it has a major impact on drag which in turn has a

major impact on powering and range.

Lastly, all designs were accomplished via the Hydrofoil Analysis and Design (HANDE) synthesis program at DTNSRDC which is explained in Appendix B. This approach was used to assure consistency in many of the engineering aspects of the problem. This synthesis model approach allowed the same algorithms to be used to estimate various weight groups. Structures were designed for all ships using common criteria and philosophy. Electrical requirements for all ships reflect the same assumptions. Ship drag and fuel loads were calculated assuming the same efficiences. And common margins were used for all ships.

The HANDE program could not be used directly for the design of the hybrid hydrofoils. A combined computer-aided and manual design procedure was used as developed at DTNSRDC. Appendix B also contains an explanation of this combined procedure.

CHAPTER III

HYDROFOIL - HYBRID COMPARISONS

A. General:

Only twenty-five point designs were incorporated into this thesis. Of these twenty-five designs, four (4) were fifty (50) knot vice forty (40) knot designs. Of the twenty-one forty (40) knot designs, only nine were hybrid designs. The remaining twelve were conventional designs.

This sparcity of data was due to constraints on both time and money. Each point design is a complete preliminary design and is quite detailed hence expensive to prosecute in terms of both time and money. Consequently, the results of the comparisons should be viewed in the light of this sparcity of data. The comparative results are tentative and subject to change when more data becomes available. It is believed that the conclusions reached in this thesis will remain generally valid but subject to refinement when more data points are included.

Also, all but two of the point designs were developed with so-called "rubber" engines. This means that propulsion horsepower figures are a direct result of the drag calculations and are not related to commercially available engine sizes.

All point designs incorporate gas turbine engines for propulsion power. Currently, gas turbine engines are available in only a very few discrete sizes. This means

that the designs requiring propulsion power at levels other than multiples of these discrete sizes will be burdened with a penalty in either cost or performance or both. This cost penalty is not expected to alter the relative results of the comparisons too severely.

In the following figures, various labels are used to denote different designs. In particular, data points are plotted with a type symbol (noted on each figure) and a following tag of the form:

$\frac{\text{FOIL LOADING}}{100}$/Payload/A number, letter R or no letter.

For example, a tag reading 9/80/R would mean this is a data point for a design of 80 T Mil P/L having 900 PSF foil loading and real engines (2-LM 2500's). No letter means the design has 'rubber' engines. A single digit number is used to consecutively denote similar designs. A two digit number is used to denote the design speed if it is other than 40 knots. In the text, the tag is preceded by the letter C or H to denote conventional or hybrid designs.

All figures in Chapter III are from the data tables in Appendix C.

B. Displacement - Price Comparisons:

The following comparative plot, Figure 3, is presented for historical reasons since it sparked this thesis and led to further analysis. We started with the idea that comparisons should be made on the basis of value returned.

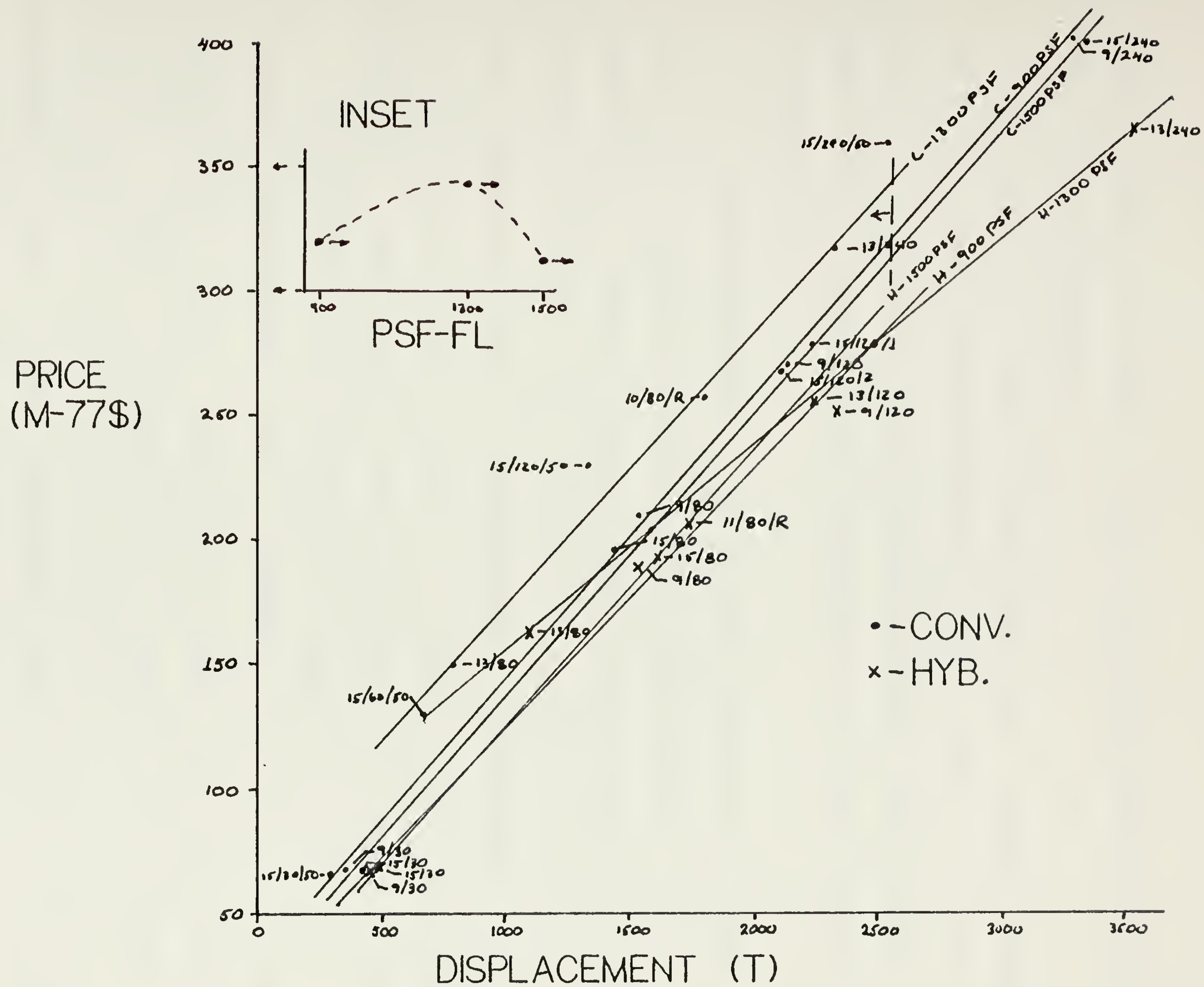

FIGURE 3 Displacement-Price Plot

Hence, Figure 3, a plot of Full Load displacement versus Price, was generated.

The data is skimpy, as mentioned, but straight lines are felt to be justified based upon the behavior of the 900 PSF and 1500 PSF conventional hydrofoil data points. Lines are for constant foil loadings for either conventional or hybrid designs.

In this simplistic plot, conclusions must be drawn with care. However certain observations appear to be justified: 1) above a displacement of approximately 1500 T, hybrids are larger than conventional hydrofoils for the same payload and speed, ignoring range differences; and 2) the increase in design speed to 50 knots from 40 knots is expensive. Also bigger does not necessarily imply better.

In general bigger means more expensive. The cost function may bend over due to economies of scale, but the general trend holds. Rarely does bigger cost you less total dollars. Figure 3 was generated to explore this concept with respect to Hybrid hydrofoils versus conventional hydrofoil craft. It was admittedly drawn from a position of ignorance but some interesting trends showed up.

There are two effects noted in Figure 3 that directed further study. The first noted was that Hybrids are segregated from conventional hydrofoil designs by both size and cost. The second was the segregation of data by foil loading.

The general assumption has been that higher foil loadings are better since they require less foil area. And in general this appears to be true. The interesting point was that the variation was nowhere near linear but approached the parabolic (see inset graph on Figure 3). Both the 900 PSF and 1500 PSF lines are quite close together whereas the 1300 PSF line is displaced significantly for both the conventional and hybrid hydrofoil designs. The data separated out so well that it was judged significant enough to merit further inquiry.

It should be noted that the two 'real engined' (2-LM 2500 engines) designs are not directly comparable to, nor consistent with the other point design data points. This is due to the change in the underlying design philosophy that resulted in actual engines being incorporated into the design vice the use of 'rubber' engines.

C. Range - Price Comparisons:

As mentioned previously, with Design Speed held constant at forty (40) knots and Payload weight held constant in four groups, Range becomes an indicator of Combat Worth. This prompted the generation of Figure 4, a plot of achievable range at a nominal thirty-five (35) knot foil borne speed versus Price.

We can note that the forty (40) knot designs, both conventional and hybrid combined, tend to group by military payload into separate fields on the graph. The 30T and 120T

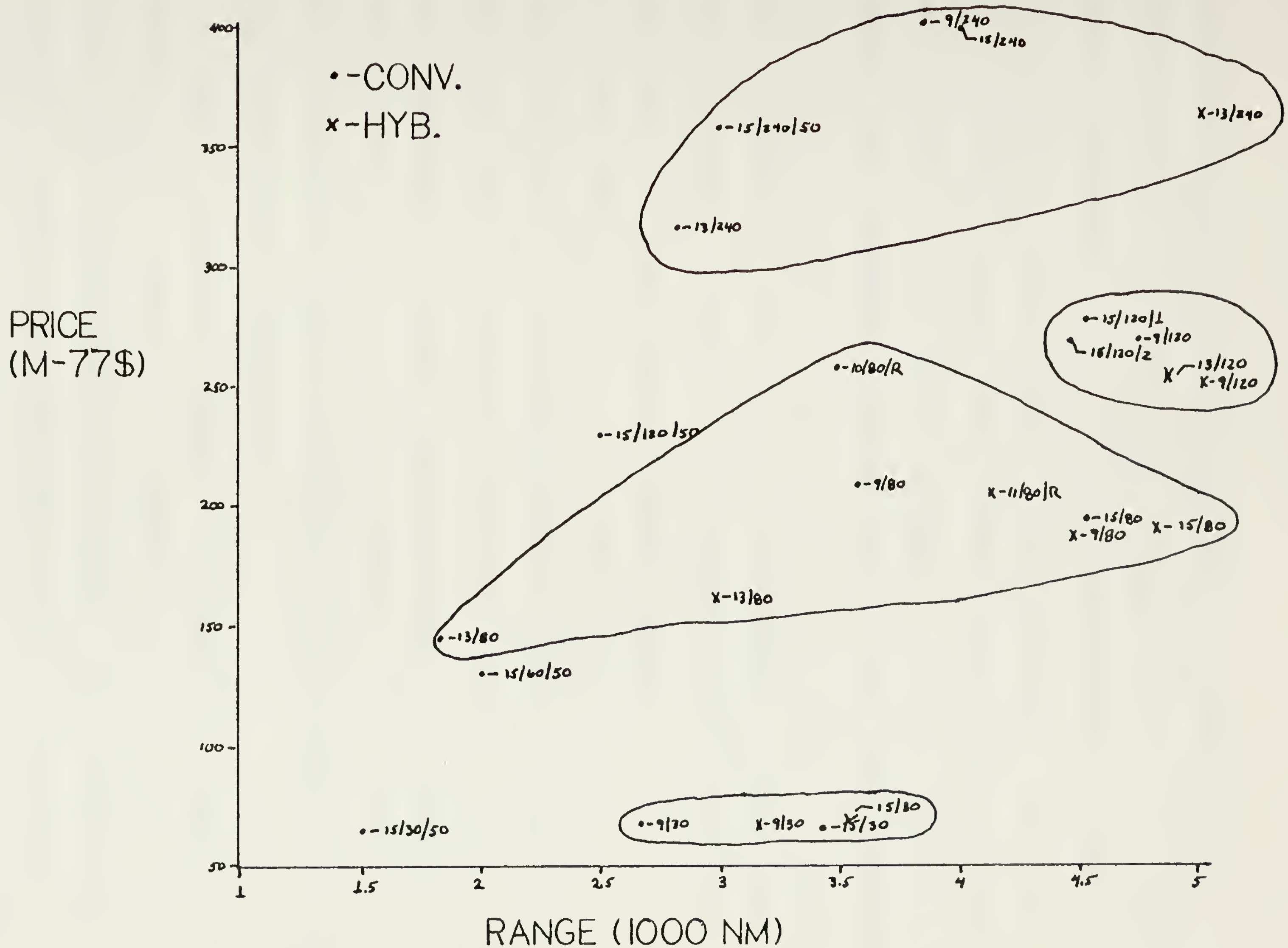

FIGURE 4 Range-Price Plot

payload groupings are nicely compact. But the 80T and 240T groupings are spread over a larger area. This spreading is believed to be a function of the number of foil loading data points included in each grouping. Both the 30T and 120T groupings have only 900 PSF and 1500 PSF data points which, as indicated in Figure 3, tend to show-up rather close together. Whereas the 80T and 240T groupings are represented by 900 PSF, 1300 PSF and 1500 PSF designs. This spreading of the group is a reflection of the trend shown in Figure 3 wherein the 1300 PSF design line deviated from the 900 PSF and 1500 PSF design lines.

This deviation of the 1300 PSF designs is believed to be an artifact of the design process and not a function of ship type such that the 1300 PSF designs drop in range hence size hence cost. However, interpolating a data point for the 1300 PSF designs as falling between the 900 PSF and 1500 PSF design points for constant payload weight and speed is an unwarranted assumption.

What is clear from Figure 4 is that Hybrid hydrofoils cannot supplant Conventional hydrofoils in all size categories. The Hybrid designs are cheaper than Conventional hydrofoil designs when ocean going ranges are required. Whereas the conventional designs are adequate when shorter ranges will be needed. What you also get from using hybrid designs is the option to purchase extra range cheaply.

D. Specific Power - Transport Fraction Comparisons:

Figure 5 is a cross-plot of two nondimensional parametric indicators of worth. The inverse of Specific Power, $\frac{1}{SP} = (\frac{M_v\ V}{P_i})$ is plotted against the Transport Fraction, $TF = (\frac{M_f + M_p}{M_v})$. An increase in TF and an increase in $\frac{1}{SP}$ are both judged to be 'good'. Hence points in the upper right quadrant are 'better' than points in the lower left quadrant.

Within the forty (40) knot collection of points, Design Speed V is essentially constant so that $\frac{1}{SP}$ measures an efficiency similar to Transport Efficiency. TF can also be thought of as an efficiency since it measures the fraction utilization of available mass for the mission related items of payload and fuel.

This figure is presented for information purposes only as it does not explicitly contain any measure of the resources devoted towards achieving these outputs. The H-11/83/R point appears to be the best shown (depending upon the relative weights of $\frac{1}{SP}$ and TF) but there is no indication shown on this plot of how much it costs to achieve this end. In a world of increasingly limited resources, the amount of resources committed towards achieving a given result should receive just as much attention as the resultant worth.

What is shown on Figure 5 is a superiority for the Hybrid designs with regard to the Transport Fraction alone. The Hybrid design data points occupy the frontier region

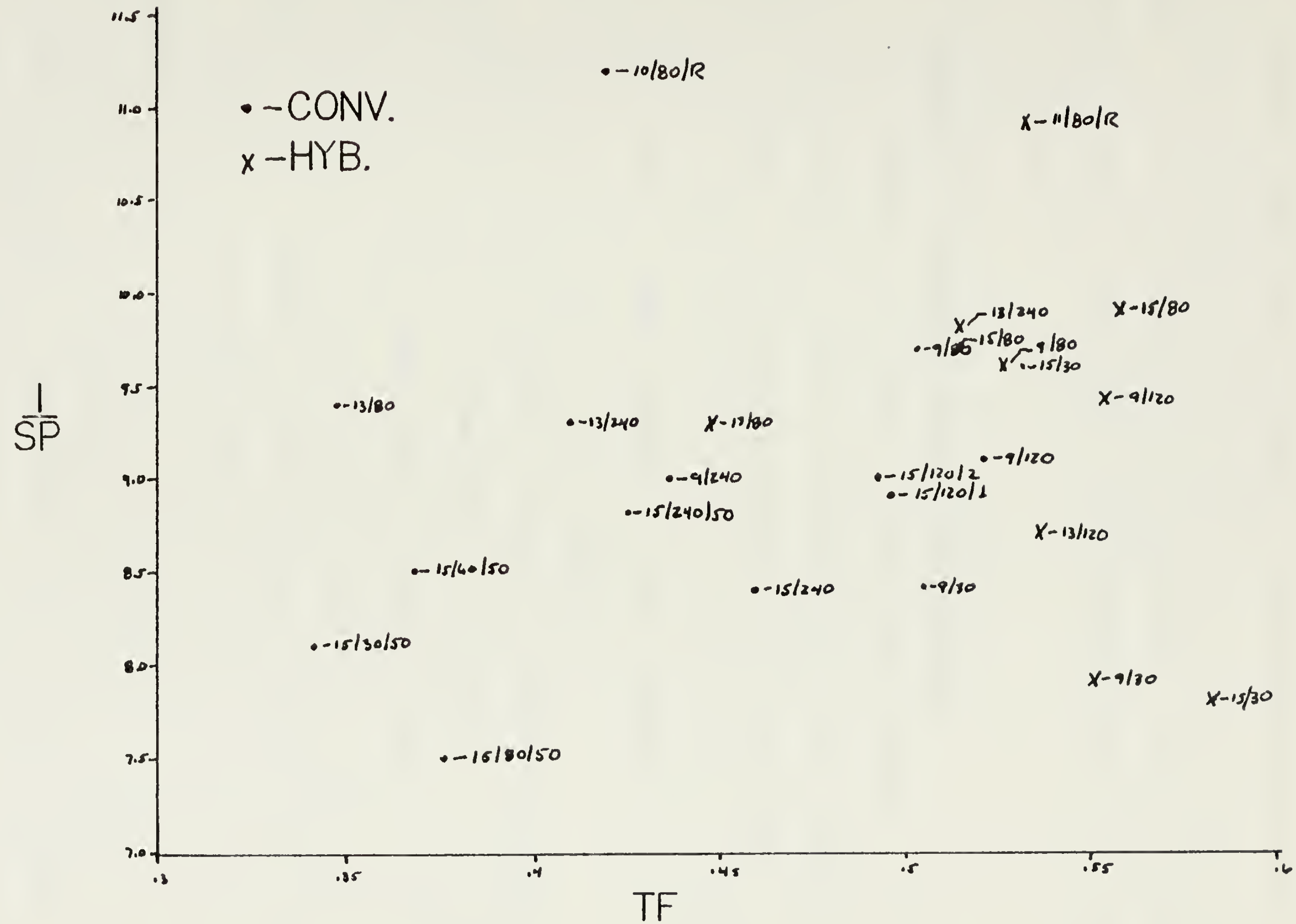

FIGURE 5 Specific Power-Transport Fraction Plot

(boundary of achievable space) with regards to TF.

We can also note on Figure 5 the penalty paid for increasing Design Speed from forty (40) knots to fifty (50) knots. This is illustrated by the fifty (50) knot designs being clustered in the lower left quadrant with low values of both $\frac{1}{SP}$ and TF.

E. Transport Fraction - Price Comparisons:

The Transport Fraction as previously defined is an efficiency measure related to payload and fuel weights. It can be used as one representation of Combat Worth. It is a fairly valid representation when the other contributor to Combat Worth, namely speed, is held constant as has been done for the most part in this thesis.

As also defined earlier, Price is a good surrogate for measuring the input or commitment of resources to a given design. This Price along with TF should yield an illustrative comparison of inputs versus outputs and give some insight into the concept of the ship as a Transfer Function.

Figure 6 on the next page is a plot of just these two parameters, Price versus TF. Here again the forty (40) knot ship data, for both hybrid and conventional designs, tends to cluster together in relatively well defined regions about the four payload weight groupings. Within each payload weight grouping, the only variable in TF is the weight of the fuel, which can be used as a very rough measure of range.

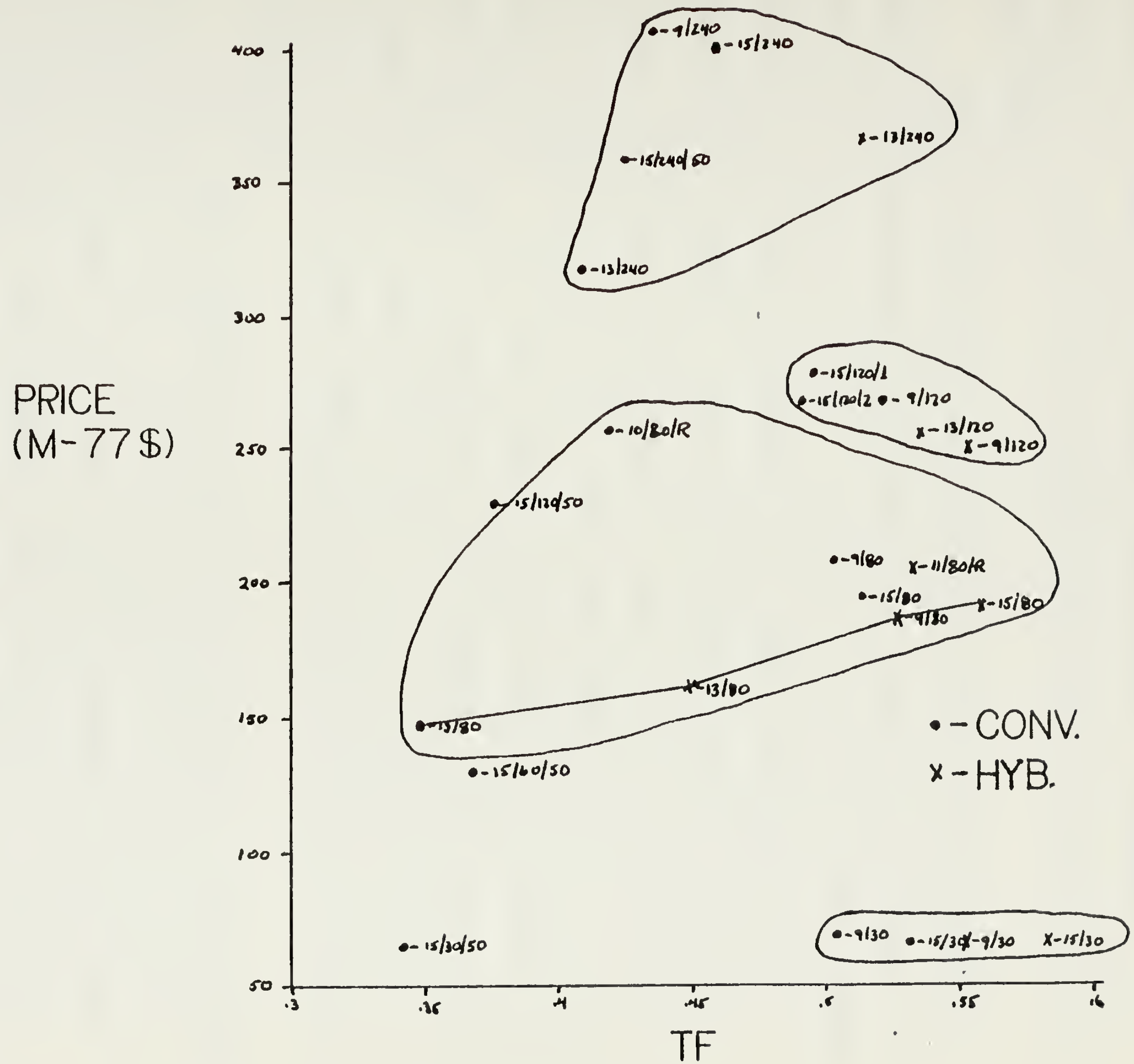

FIGURE 6 Transport Fraction-Price Plot

When an engineer designs a warship, he aims to have the design perform the indicated mission tasks at the least cost. He aims for an efficient design. In regards to Figure 6, an efficient design has a high TF coupled with a low Price.

Design efficiency can be illustrated by using the 80T Mil P/L grouping on Figure 6. A curve is defined for this grouping by the four designs C-13/80, H-13/80, H-9/80 and H-15/80 which delineates the lower boundary of the 80T Mil P/L space. If we say that 80T of Mil P/L is required to perform the mission, then the aim of producing an efficient design will force the design to lie on or near this curve. The exact point on the curve will depend upon how much range we require or can afford. Any design falling significantly above this curve is not efficient since it would have a higher Price for the same TF than a design on the curve.

The lower boundary curve can be defined as the Trade-off Boundary curve. What this Trade-off Boundary curve shows us is that increasing the fuel weight costs money. However, this added expense can be reduced by utilizing Hybrid designs when longer ranges hence more fuel is required. We note in passing that three of the four design points defining the Trade-off Boundary curve are for Hybrid designs. In fact, for high TF values, Hybrid designs are consistently cheaper than Conventional hydrofoil designs.

The preceding was based on the 80T Mil P/L grouping due to its having a more complete data set. However, the concepts, trends and conclusions are not contradicted by any of the other three data groupings, although their data set is admittedly less complete.

We can also note in Figure 6 that the variations with foil loading, evidenced in previous figures, are still evident.

F. Transport Efficiency - Price Comparisons:

Transport Efficiency (TE) is yet another nondimensional representation of Combat Worth. It is defined as $TE = \frac{(M_f + M_p) \cdot V}{P_i}$ and attempts to combine the three elements of Combat Worth into a single parameter.

Figure 7 on the next page reflects the Transfer Function idea by plotting TE, as output, against Price, as input. Here again the data groups nicely about the various values of Mil P/L weight.

The discussion in Section E preceding, concerning the Trade-off Boundary curve is equally valid when applied to the data sets in Figure 7. Each grouping displays consistent behavior and exhibits the flattened cost function associated with Hybrid designs.

We can also note on Figure 7 the penalty, in terms of TE, that is paid for designing to a fifty (50) knot vice forty (40) knot Design Speed.

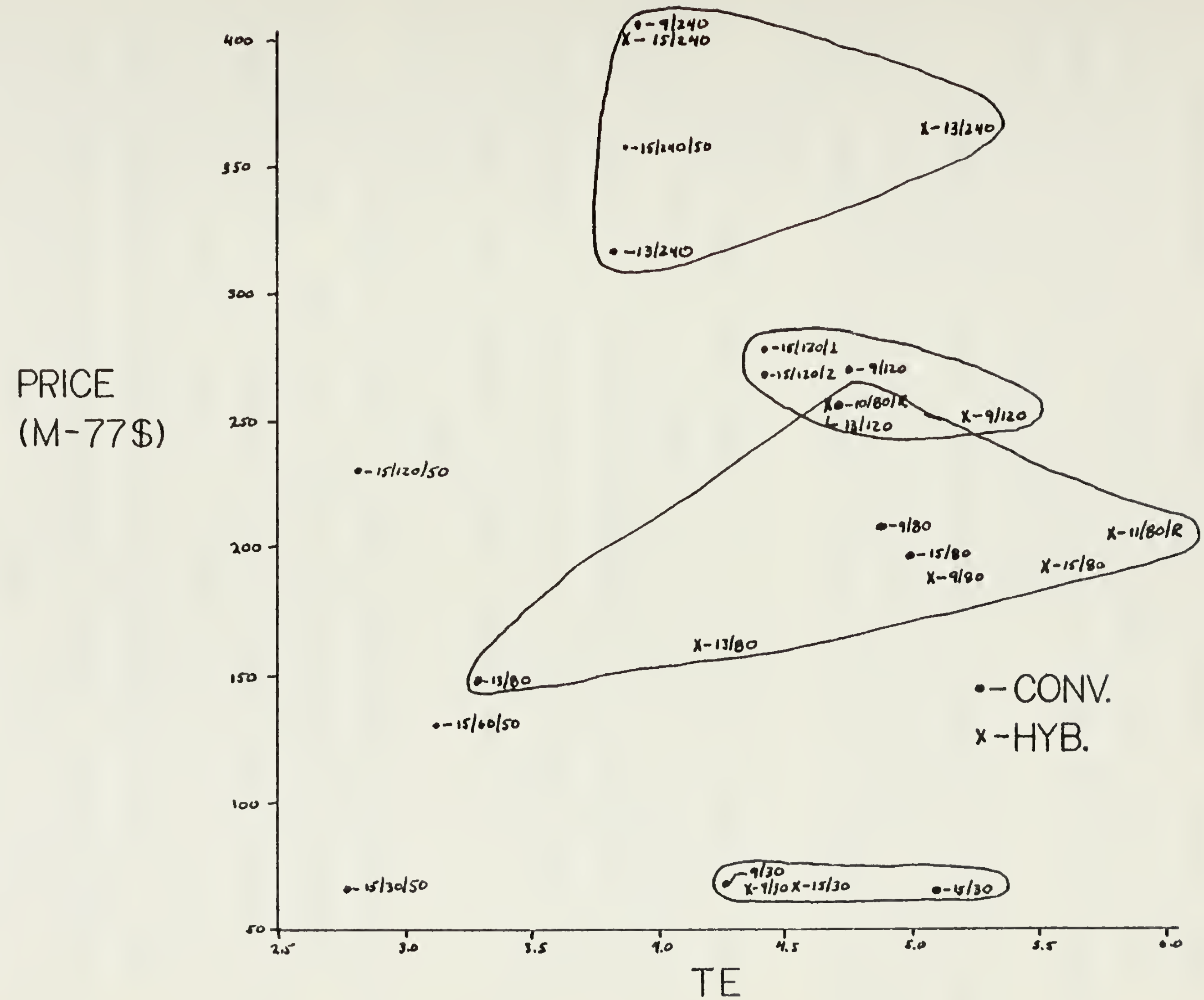

FIGURE 7 Transport Efficiency-Price Plot

G. Transport Fraction - Transport Efficiency Comparisons:

Both TF and TE are measures of output, i.e. surrogates for Combat Worth. A cross-plot of the two is not illustrative of a ship design's efficiency since cost is not explicitly included. We do expect a high TF to be accompanied by a high TE and vice-versa.

Figure 8 on the next page is a cross-plot of TF versus TE and does allow some interesting observations. Note that high values of TF and high values of TE are considered to be 'good'.

First note that there are no obvious trends by foil loading. The data is much too scattered. Secondly, note that a high TF is usually accompanied by a high TE, but the correspondence is not one to one. This shows that while TF or TE alone may represent Combat Worth, neither should be used exclusive of the other.

Also worthy of note is that the data is loosely grouped by ship type. There are three distinct groups composed respectively of: 1) The fifty (50) knot Conventional hydrofoil designs being lowest; 2) The forty (40) knot Conventional hydrofoil designs being intermediate; and 3) The forty (40) knot Hybrid hydrofoil designs being highest, in terms of combined TF and TE values. There is quite a bit of overlap between the groups so conclusions about individual designs should be drawn with great care.

By referring back to Figure 6 and Figure 7 it can be seen that the indicated superiority, in TF and TE, for the

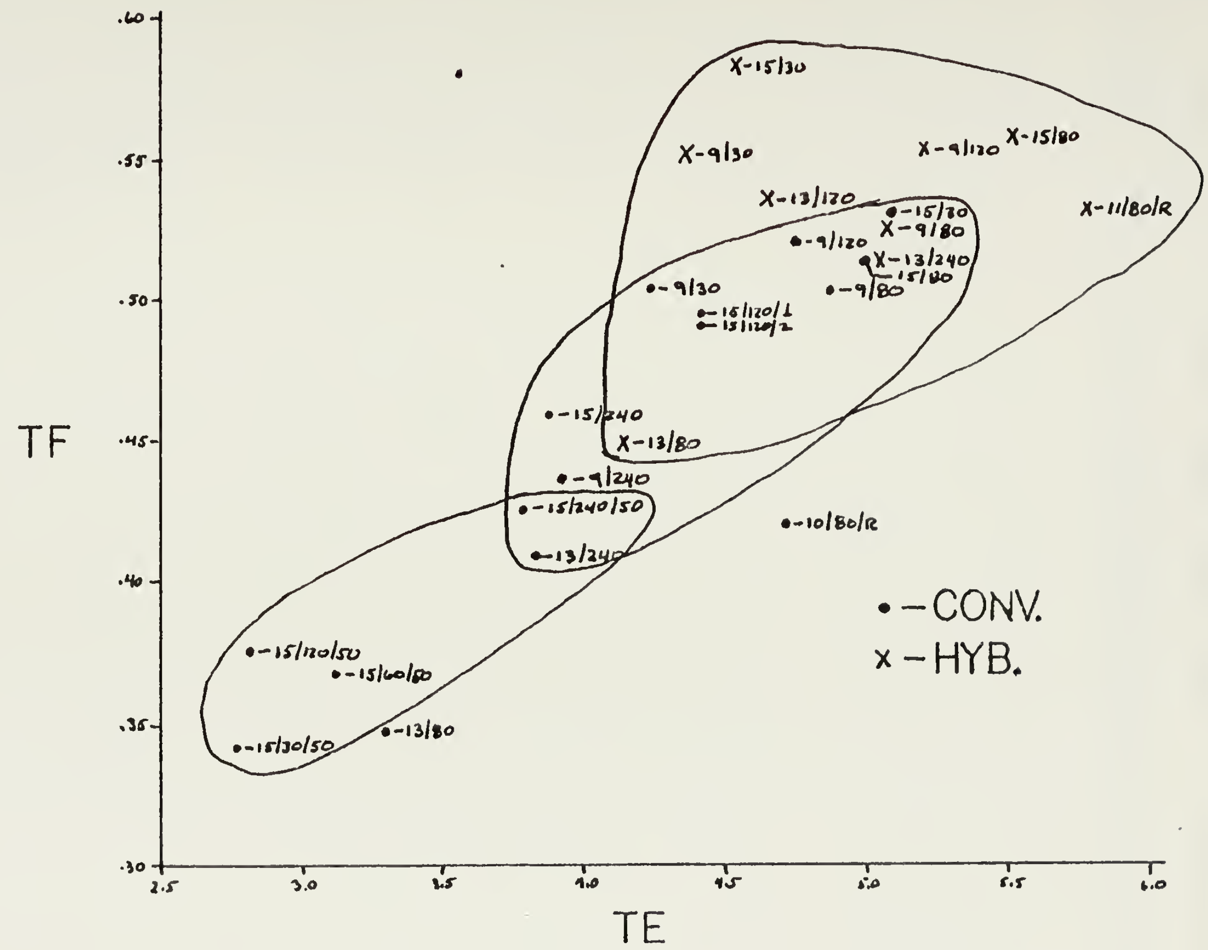

FIGURE 8 Transport Fraction-Transport Efficiency Plot

Hybrid hydrofoil designs is purchased at some cost. But as is also indicated, this superiority (primarily in Range) can be purchased at lower additional cost, by using hybrid designs, than if only conventional designs were used.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

A. General:

The foregoing chapters and graphs were presented to illustrate a comparative vehicle technique that views the vehicle as a Transfer Function which is capable of converting resources into Combat Worth. This technique was exemplified by comparing the Hybrid hydrofoil to Conventional hydrofoil designs.

It was shown that the Hybrid hydrofoil concept can broaden the options available to the ship designer by allowing him to increase the achievable Range of the ship design, at lower cost, than can be achieved by the sole utilization of Conventional hydrofoil designs. This lower cost per mile of Range was evident when certain specific parameters were used to evaluate the Combat Worth in terms of the amount of committed resources.

B. Other Factors:

There are obviously other factors that should enter into a comparison between vehicle types than those that have been presented. Some of these, such as seakeeping, were deliberately not addressed because the variation in them between a hybrid and conventional hydrofoil was small or nonexistent hence not useable to draw distinctions between the two ship types. Both the hybrid and the conventional hydrofoil enjoy relatively good seakeeping abilities.

Seakeeping capabilities degrade with increases in top speed as is well known. The differences in degradation between these two ship types is not known. However, it is known that the degradation in seakeeping with speed for other ship types, such as conventional monohull displacement ships, is greater than with either hybrid or conventional hydrofoils.

Another factor not varied in this thesis is that of 'Technology and Standards'. All designs utilized in this thesis were designed to the same level of 'Technology and Standards'. Employing different levels of Technology and/or different design Standards in different ship designs in the comparison would unduly complicate matters. If the same Technology and Standards are employed in designs of other vehicle types, the design trade-offs between ship types becomes apparent.

For example, a comparison of conventional displacement monohull and hydrofoil craft, employing the same 'Technology and Standards' (Graham (16)), clearly shows that hydrofoil craft trade-off payload capacity for enhanced seakeeping abilities.

Other factors that should be fed into a comparison can be termed 'intangibles'. This term is used to mean that either the parameter itself or its contribution to the vessel's Combat Worth is not quantifiable. For the hybrid designs, these intangibles may be: lower 'take-off' speed, lower foil borne speed, increased navigational draft and

lack of a dry foil retraction system. This list is by no means exhaustive, but it does illustrate the additional items that must be considered before choosing between either a hybrid or conventional hydrofoil design.

C. Recommendations:

The first recommendation is to continue the generation of consistent hybrid and conventional hydrofoil designs in order to broaden the data base. This will allow both the confirmation or modification of the results of this thesis and the further exploration of effects such as variations in the foil loading.

Secondly, it is strongly urged that the conventional research hydrofoil USS High Point (PCH-1) be modified into the hybrid configuration by the addition of a buoyancy fuel tank to the foil system. This ship, while quite small, is admirably suited for this modification and the expense should not be great. This modification will allow existing analyses to be verified and possible new advantages or disadvantages of this vehicle type may be uncovered. The PCH-1 would provide a well documented base line for performance evaluation.

And thirdly, it is recommended that further work be undertaken to quantify the concept of the ship as a Transfer Function. If this technique can be quantified, it may be possible to manipulate it such that rational ship comparisons will become easier to make.

D. Concluding Remarks:

The Hybrid hydrofoil vehicle type has been shown to be an attractive alternative to the Conventional hydrofoil vehicle type when long ranges are required. This is due primarily to its combination of ocean going range with the speed and seakeeping qualities of the Conventional hydrofoil.

The inclusion of Hybrid vehicles into the ship designer's repertoire broadens the options available to him when specific design requirements are to be met.

In spite of the fact that this thesis focuses on an advanced concepts vehicle, we must remember that the mere existence of advanced concepts is by no means assurance that they will be adopted. "The problem of adopting innovations by large bureaucracies such as the Navy is a complex one. Thus, which innovation will be adopted into future surface warships will be as much a bureaucratic/sociological issue as a technological one" Leopold (6).

Regardless of who is making the decisions - options must be available so that the best (highest utility) designs can be implemented. Hybrid designs increase the range of options available.

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APPENDIX A

COST ESTIMATING ROUTINES

Construction Cost:

Algorythms used to estimate the cost of a ship design vary in sophistication from the simple, dollars per pound of light ship weight, to the very complex ones employed by ship builders to justify bids on Navy and commercial contracts.

In the Navy, ship construction money has a political source in Congress. Hence, cost estimating routines (CER's) for Naval ships are treated as sensitive data and access to these CER's is severely restricted.

In order to counter the access restriction on these CER's for use in this thesis, the specific CER's are disguised and presented in a lumped form in the following Table A-1.

The CER's used in this thesis were adapted from the CER's developed by the Advanced Naval Vehicle Concepts Evaluation (ANVCE) study (Ref. (12)), as employed in the Hydrofoil Analysis and Design (HANDE) ship synthesis program at David W. Taylor Naval Ship Research and Development Center (DTNSRDC).

The particular factors in each CER were derived from regression analyses of either past returned cost data or from existing ship construction cost data.

The CER's use weight group amounts as entering argu-

ments except for Groups 2, 8 and 9. Group 2 uses propulsion horsepower in metric horsepower units. Groups 8 and 9 use the dollar sum amounts of Groups 1 through 7 inclusive. Also the particular factors employed reflect the following assumptions about the design to be evaluated: 1) High technology equipments and processes; 2) Sophisticated weapons suites; 3) That the design is for the lead ship in a class; and 4) That the design is a hydrofoil vehicle type.

It is felt that the Price figures may be a bit too high, but that the relative variations between competing designs should be accurate.

Operating Costs:

Although operating costs were not factored into any of the comparisons, they were estimated and included in the data tables of Appendix C for information purposes.

The basic operating CER was adapted from Mandel (13) and accounts for differences in number of crew and fuel weight needed for an arbitrary 96,000 Nm yearly steaming distance. This CER has the form of:

$$OC = Nc \cdot \$55{,}000 + M_f \cdot \frac{96{,}000}{2R} \cdot .135\ \$/kg.$$

Femenia (19) developed estensive CER's for estimating the operating costs of various propulsion plants. He included Maintenance and Repair costs, Insurance costs, lube Oil costs and various other costs. These were not included in the Operating Cost CER used in this thesis since some were not applicable and the rest were direct functions of the operating profile. And as was mentioned previously,

ships of the same payload class are assumed to have the same operating profile thereby not contributing any differences to the Operating Costs.

TABLE A-1

COST ESTIMATING ROUTINES

Group	Function	Item
1	$125.9196(W100)^{.772}$	Structures
2	$1.8565(Pi)^{.808}$	Propulsion
3	$101.2442(W300)^{.910}$	Electrical
4	$499.0897(W400)^{.617}$	Navigation & Comm.
5-567	$426.3112(W500-567)^{.782}$	Auxiliaries Less Foils
567	$340.7974(W567)^{.782}$	Foil System
6	$121.5407(W600)^{.784}$	Electronics
7	$18.8483(W700)^{.987}$	Weapons
8	$0.4952(\Sigma\$1\text{-}7)^{1.099}$	Design & Eng.
9	$1.6378(\Sigma\$1\text{-}7)^{.839}$	Construction Services
M	108. (Wm)	Margins

entering arguments in metric tons and metric horsepower

assumes: Lead ship, high technology, sophisticated weapons for hydrofoils ship types.

APPENDIX B

HANDE SYSTHESIS MODEL

The Hydrofoil Analysis and Design (HANDE) computer program (20) was developed over several years. It contains a collection of computational modules - each limited to a single technology.

A data bank contains detailed information on past hydrofoil designs. These previous designs are altered in the synthesis portion of the program to produce a new design. Figure B-1 shows each of the modules of the program and the computational procedure. Each synthesis module uses designer-provided data to perform calculations as they would be done manually. Additionally, the design procedure is user controlled.

While the conventional hydrofoils were designed using the HANDE program directly, the Hybrids, with their buoyancy/fuel tanks, were designed using a modified procedure illustrated in Figure B-2. This unpublished procedure was developed at DTNSRDC by J. King, which combines manual and computer-aided calculations. Hydrofoil system drag, ship subsystem weights, and propulsion system characteristics were estimated using the computer program. The drag for the notional tanks was added to the hydrofoil drag to yield total drag, which, in turn, was used by the computer to determine required power and to estimate performance.

Tank structural weights, weights of fuel bladders, and weights of additional electrical, auxiliary, and outfitting requirements were estimated manually. The computer program was used to estimate the additional weight of foil/strut assemblies required for support of the tanks.

Using only HANDE generated designs in this thesis ensures that all conventional hydrofoil designs are technologically consistent. Since the hybrid design procedure follows the HANDE program, the same assumptions can be made with regard to hybrid designs.

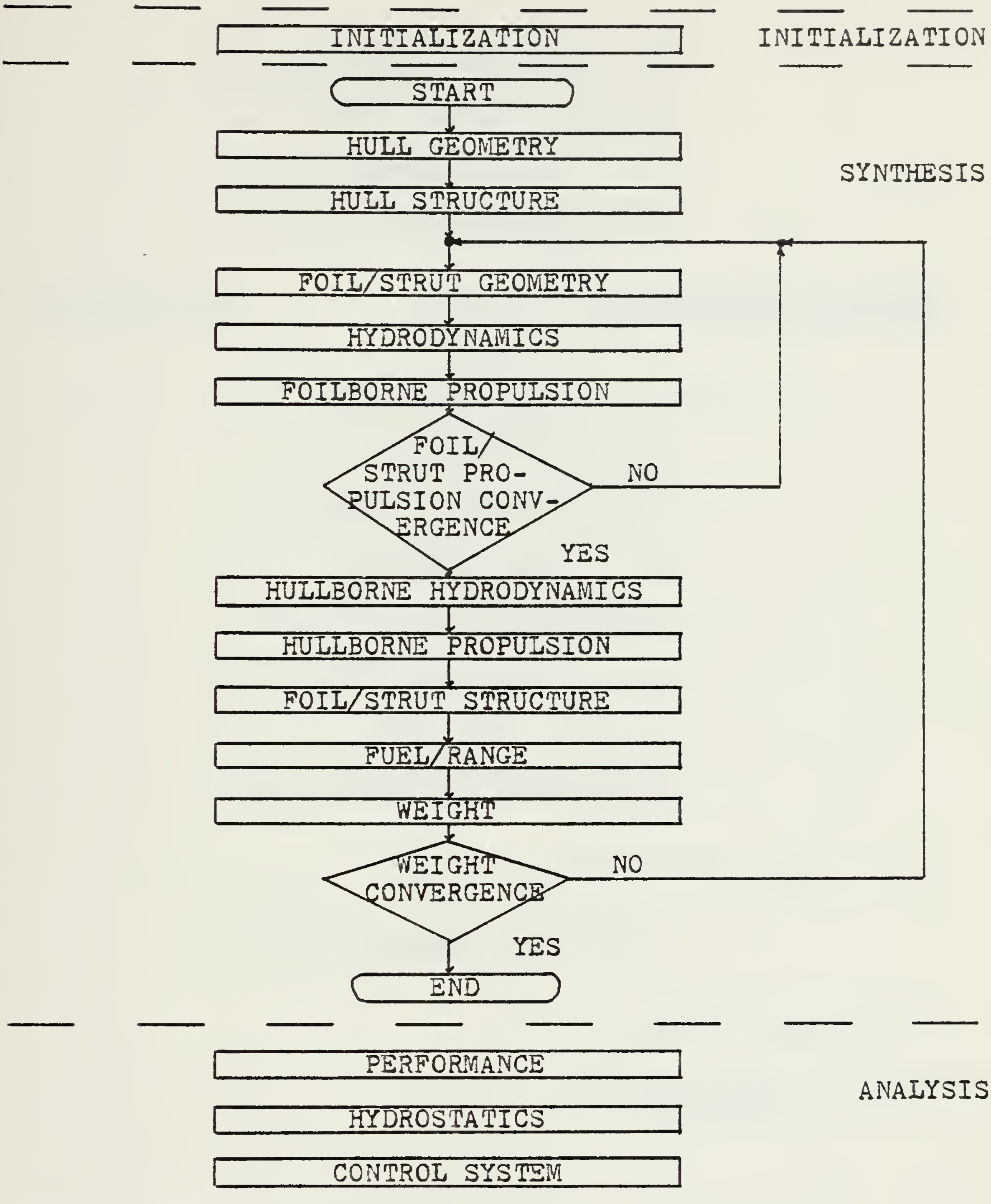
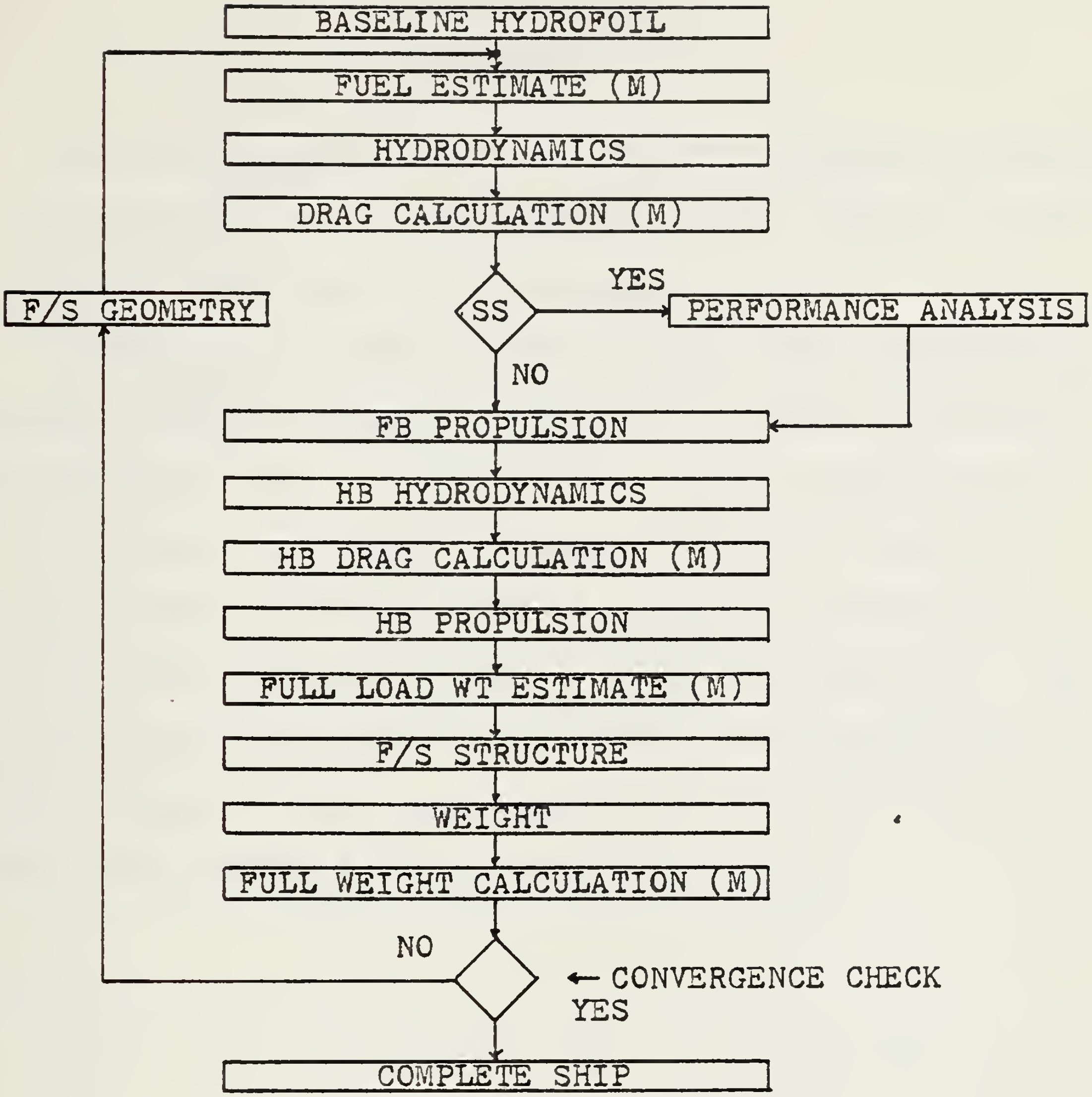


FIGURE B1 HANDE analysis modules



(M)=MANUAL CALCULATION

SS =SEA STATE PERFORMANCE CRITERION

FIGURE B2 Buoyancy/fuel tank hydrofoil calculation procedure

APPENDIX C

SHIP DATA

Weights, Ranges, Speeds and other information used for the comparisons of the ship designs in this thesis are presented for reference in this section.

Table C-1 is a general data summary sheet arranged by payload and foil loading. Tables C-2 through C-6 present more detailed data on each design. Design nomenclature is that utilized at DTNSRDC, for cross reference purposes. The four fifty (50) knot designs are from reference (10). The two real engined designs are from reference (21). All of the design data was derived either directly from the HANDE program outputs or, as in the real engine design case, from HANDE program outputs modified slightly.

TABLE C-1

DESIGN SUMMARY SHEET

Ship	Foil Loading	Payload	V	2R/Ve	Displacement	Price
C-9/30	900 PSF	30T	42 kts	2719Nm/35kts	402T	68.9M$
C-9/80	900	80	40	3576/35	1531	209.9
C-9/120	900	120	42	4766/35	2135	270.6
C-9/240	900	240	42	3848/35	3217	401.8
H-9/30	900	30	40	3157/35	450	65.4
H-9/80	900	80	40	4474/35	1513	188.2
H-9/120	900	120	40	5032/35	2324	251.5
C-10/80/R	985	86	40	3490/35	1796	258.6
H-11/80/R	1107	83	40	4140/35	1738	206.5
H-13/120	1275	120	40	4875/35	2248	255.6
C-13/80	1300	80	41.5	1829/35	785	145.9
C-13/240	1300	240	40	2832/35	2309	317.5
H-13/80	1300	80	41.5	2970/35	1091	162.5
H-13/240	1300	240	40	5011/35	3527	365.2
C-15/30	1500	30	40	3428/35	422	66.5
C-15/80	1500	80	40	4530/35	1441	195.6
C-15/120/1	1500	120	42	4531/35	2217	279.6
C-15/120/2	1500	120	42	4454/35	2101	269.1
C-15/240	1500	240	40	4022/35	3344	400.9
H-15/30	1500	30	40	3520/35	484	67.2
H-15/80	1500	80	40	4820/35	1606	192.2
C-15/30/50	1500	30	50	1500/44	293	65.3
C-15/60/50	1500	60	50	2000/44	663	131.0
C-15/120/50	1500	120	50	2500/44	1326	230.2
C-15/240/50	1500	240	50	3000/44	2570	359.0

TABLE C-2

SHIP		C-9/30	C-15/30	H-15/30	H-9/30
Payload Mass-	Mp	30 T	30	30	30
Vehicle Mass-	Mv	402 T	422	484	450
Fuel Mass-	Mf	173 T	195	252	218
FB Prop. Power-	Pi	14022 MH_p	12276	17327	15851
Design Speed-	V	42 kt	40	40	40
FB Endurance Sp.-	Ve	35 kt	35	35	35
Op. Range-	2R	2719 Nm	3428	3520	3157
Foil Loading-	FL	900 PSF	1500	1500	900
Lift Ratio (Dyn/Buoy)		90/10	95/5	56/44	51/49
Crew (O/C/E-Total)	Nc	5/4/12-21	5/4/12-21	5/4/12-21	5/4/12-21
Tank Size		-	-	200 T	200
Op. Cost-	OC	1955(K$-77)	1904	2100	2066
Specific Power-SP/$\frac{1}{SP}$		.119/8.4	.104/9.6	.128/7.8	.120/7.9
Transport Fraction-	TF	.505	.532	.583	.551
Transport Efficiency-	TE	4.24	5.10	4.54	4.36

TABLE C-2 (Con't.)

SHIP			C-9/30	C-15/30	H-15/30	H-9/30
W100		(MT)	49.7	49.9	62.4	62.0
	$1	(K$)	2569	2576	3062	3047
Pi		(MHP)	14022	12276	17327	15851
	$2	(K$)	4162	3738	4938	4596
W300		(MT)	8.6	8.7	9.0	9.0
	$3	(K$)	717	725	748	748
W400		(MT)	11.4	11.5	11.3	11.3
	$4	(K$)	2240	2252	2228	2228
W500-567		(MT)	16.3	17.0	15.8	15.4
	$5	(K$)	3781	3908	3690	3617
W567		(MT)	44.7	40.3	29.6	29.1
	$567	(K$)	6653	6135	4820	4756
W600		(MT)	17.6	18.2	18.6	18.2
	$6	(K$)	1151	1182	1202	1182
W700		(MT)	9.7	9.7	9.7	9.7
	$7	(K$)	178	178	178	178
	Σ $1-7	(K$)	21451	20694	20866	20352
Design & Eng. $8		(K$)	28513	27409	27659	26912
Const. Services $9		(K$)	7057	6843	6891	6748
Wm		(MT)	26.7	26.8	27.9	26.9
	$M	(K$)	2888	2894	3013	2902
Total Const. Cost		(K$)	59905	57840	58429	56914
15% Profit		(K$)	8986	8676	8764	8537
	PRICE	(K$)	68,891	66,516	67,193	65,451
HANDE NAME			S/900/40	S/1500/400	S-T-1500 -270/200	S-T-200

TABLE C-3

SHIP		C-13/80	H-13/80	C-9/80	C-15/80	H-9/80	H-15/80
Payload Mass	Mp	80 T	80	80	80	80	80
Vehicle Mass	Mv	785 T	1091	1531	1441	1513	1606
Fuel Mass	Mf	193 T	410	692	661	731	816
FB Prop. Power	Pi	24000MHP	34194	44162	41441	43824	45294
Design Speed	V	41.5kt	41.5	40	40	40	40
FB Endurance Sp.	Ve	35 kt	35	35	35	35	35
Op. Range	2R	1829Nm	2970	3576	4530	4474	4820
Foil Loading	FL	1300PSF	1300	900	1500	900	1500
Lift Ratio(Dyn/Buoy)		92/8	57/43	88/12	94/6	53/47	59/41
Crew(O/C/E-Total)	Nc	6/5/48-59	6/5/48-59	5/5/48-58	5/5/48-58	5/5/48-58	5/5/48-58
Tank Size		-	400 T	-	-	600	600
Op. Cost	OC	4638K$	5067	5743	5115	5303	5425
Specific Power	SP/$\frac{1}{SP}$	.106/9.4	.108/9.3	.103/9.7	.103/9.7	.104/9.6	.101/9.9
Transport Fraction	TF	.348	.449	.504	.514	.526	.558
Transport Efficiency	TE	3.29	4.15	4.88	4.99	5.07	5.52

TABLE C-3 (Con't)

SHIP			C-13/80	H-13/80	C-9/80	C-15/80	H-9/80	H-15/80
W100		(MT)	121.5	147.3	193.1	187.0	221.8	221.0
	$1	(K$)	5121	5942	7323	7144	8150	8128
Pi		(MHP)	24000	34194	44162	41441	43824	45294
	$2	(K$)	6425	8553	10517	9990	10452	10734
W300		(MT)	18.2	18.4	21.6	21.6	21.8	21.9
	$3	(K$)	1419	1433	1659	1659	1672	1679
W400		(MT)	45.6	45.2	49.2	49.2	48.8	48.8
	$4	(K$)	5269	5241	5522	5522	5495	5495
W500-567		(MT)	59.6	55.8	93.2	93.2	89.0	89.5
	$5	(K$)	10422	9899	14785	14785	14261	14324
W567		(MT)	98.3	122.5	172.6	134.4	99.6	108.3
	$567	(K$)	12322	14636	19136	15736	12449	13292
W600		(MT)	49.7	49.1	72.2	72.2	72.5	72.8
	$6	(K$)	2598	2574	3482	3482	3493	3505
W700		(MT)	15.9	15.9	15.9	15.9	15.9	15.9
	$7	(K$)	289	289	289	289	289	289
	Σ$1-7	(K$)	43865	48567	62713	58607	56261	57446
Design&Eng.	$8	(K$)	62585	69995	92699	86051	82273	84180
Const. Serv.	$9	(K$)	12853	13999	17348	16390	15837	16117
Wm		(MT)	69.9	81.0	90.5	83.7	86.2	87.2
	$M	(K$)	7551	8748	9774	9040	9310	9418
Total Const. Cost		(K$)	126854	141309	182534	170088	163681	167161
15% Profit		(K$)	19028	21196	27380	25513	24552	25074
	PRICE	(K$)	145,882	162,505	209.914	195,601	188,233	192,235
HANDE NAME			40/12/1300	I-T-400	I/900/1350	I/1500/1350	I-900-600	I-1500-600

TABLE C-4

SHIP		C-9/120	C-15/120/1	C-15/120/2	H-9/120	H-13/120
Payload Mass	Mp	120 T	120	120	120	120
Vehicle Mass	Mv	2135 T	2217	2101	2324	2248
Fuel Mass	Mf	994T	980	913	1168	1084
FB Prop. Power	Pi	68592MHP	72832	68489	68943	72029
Design Speed	V	42 kt	42	42	40	40
FB Endurance Sp.	Ve	35 kt	35	35	35	35
Op. Range	2R	4766 Nm	4531	4454	5032	4875
Foil Loading	FL	900 PSF	1500	1500	900	1275
Lift Ratio(Dyn/Buoy)		82/18	90/10	90/10	48/52	49/51
Crew(O/C/E-Total)	Nc	10/6/68-84	10/6/68-84	10/6/68-84	10/6/68-84	10/6/68-84
Tank Size		-	-	-	1000 T	1000
Op. Cost	OC	7372 K$	7475	7326	7683	7555
Specific Power	SP/$\frac{1}{SP}$	.110/9.1	.112/8.9	.111/9.0	.106/9.4	.115/8.7
Transport Fraction	TF	.522	.496	.492	.554	.536
Transport Efficiency	TE	4.76	4.42	4.42	5.21	4.66

TABLE C-4 (Con't)

SHIP		C-9/120	C-15/120/1	C-15/120/2	H-9/120	H-13/120
W100	(MT)	231.9	239.0	231.9	266.8	268.4
$1	(K$)	8435	8634	8435	9400	9443
Pi	(MHp)	68592	72832	68489	68943	72029
$2	(K$)	15011	15756	14992	15073	15615
W300	(MT)	25.0	25.4	25.0	25.6	25.6
$3	(K$)	1895	1922	1895	1936	1936
W400	(MT)	62.3	62.6	62.3	62.1	62.1
$4	(K$)	6388	6407	6388	6376	6376
W500-567	(MT)	114.9	117.8	114.9	112.1	112.1
$5	(K$)	17414	17757	17414	17081	17081
W567	(MT)	253	273.5	254.1	175.8	188
$567	(K$)	25807	27428	25895	19413	20459
W600	(MT)	88.1	89.9	88.1	90.5	90.5
$6	(K$)	4070	4135	4070	4157	4157
W700	(MT)	22.4	22.4	22.4	22.4	22.4
$7	(K$)	405	405	405	405	405
$\Sigma$$1-7	(K$)	79425	82444	79494	73841	75472
Design&Eng. $8	(K$)	120180	125210	120295	110928	113623
Const. Serv.$9	(K$)	21151	21823	21166	19896	20264
Wm	(MT)	135	126.4	121	129.7	119.4
$M	(K$)	14580	13651	13068	14002	12845
Total Const. Cost	(K$)	235336	243128	234023	218667	222254
15% Profit	(K$)	35300	36469	35103	32800	33338
PRICE	(K$)	270,636	279,597	269,126	251,467	255,592
HANDE NAME		M/40/900	M/1500/40 2000T	M/1500/40 1900T	R-T-1000	D-T-1000 MOD

TABLE C-5

SHIP		C-9/240	C-13/240	H-13/240	C-15/240
Payload Mass	Mp	240 T	240	240	240
Vehicle Mass	Mv	3217T	2309	3527	3344
Fuel Mass	Mf	1161 T	707	1577	1299
FB Prop. Power	Pi	104672MHp	69079	100454	110717
Design Speed	V	42 kts	40	40	40
FB Endurance Sp.	Ve	35 kts	35	35	35
Op. Range	2R	3848 Nm	2832	5011	4022
Foil Loading	FL	900 PSF	1300	1300	1500
Lift Ratio (Dyn/Buoy)		81/19	90/10	59/41	90/10
Crew(O/C/E-Total)	Nc	14/12/114-140	14/12/114-140	14/12/114-140	14/12/114-140
Tank Size		-	-	1200 T	-
Op. Cost	OC	11,682K$	10,995	11,853	11,963
Specific Power	$SP/\frac{1}{SP}$	.111/9.0	.107/9.3	.102/9.8	.119/8.4
Transport Fraction	TF	.436	.410	.515	.460
Transport Efficiency	TE	3.92	3.82	5.05	3.88

TABLE C-5 (Con't)

SHIP			C-9/240	C-13/240	H-13/240	C-15/240
W100		(MT)	353.8	311.7	390	351.7
	$1	(K$)	11688	10599	12601	11634
Pi		(MHP)	104672	69079	100454	110717
	$2	(K$)	21121	15097	20430	22101
W300		(MT)	34.3	33.4	33.6	34.3
	$3	(K$)	2526	2466	2479	2526
W400		(MT)	69.8	68.6	68.6	69.8
	$4	(K$)	6852	6779	6779	6852
W500-567		(MT)	179.7	166.7	166.7	179.7
	$5	(K$)	24705	23296	23296	24705
W567		(MT)	451.3	263.8	332.0	435
	$567	(K$)	40578	26664	31917	39427
W600		(MT)	132.9	125	127.3	132.9
	$6	(K$)	5618	5354	5431	5618
W700		(MT)	77	77	77	77
	$7	(K$)	1372	1372	1372	1372
	Σ $1-7	(K$)	114460	91627	104305	114236
Design & Eng.	$8	(K$)	179573	140619	162143	179187
Const. Serv.	$9	(K$)	28739	23845	26584	28692
Wm		(MT)	246.9	184.8	227.5	245.0
	$M	(K$)	26665	19961	24565	26460
Total Const.	Cost	(K$)	349437	276052	317597	348575
15% Profit		(K$)	52416	41408	47640	52286
	PRICE	(K$)	410,853	317,460	365,237	400,861
HANDE NAME			L/40/900	240/FBS/40	L-T-1200	L/40/1500

TABLE C-6

SHIP		C-10/80/R	H-11/80/R	C-15/30/50	C-15/60/50	C-15/120/50	C-15/240/50
Payload Mass	Mp	86 T	83	30	60	120	240
Vehicle Mass	Mv	1796 T	1738	293	663	1326	2570
Fuel Mass	Mf	668 T	842 T	70	184	379	855
FB Prop. Power	Pi	44610MHp	44610	12600	27300	62000	101000
Design Speed	V	40 kts	40	50	50	50	50
FB Endurance Speed	Ve	35 kts	35	44	44	44	44
Op. Range	2R	3490 Nm	4140	1500	2000	2500	3000
Foil Loading	FL	985 PSF	1107	1500	1500	1500	1500
Lift Ratio(Dyn/Buoy)		91/9	60/40	UNK	UNK	UNK	UNK
Crew (O/C/E-Total	Nc	6/5/48-59	6/5/48-59	5/4/12-21	6/5/34-45	10/6/68-84	14/12/114-140
Tank Size		-	600 T	-	-	-	-
Op. Cost	OC	5,771	5,930	1,771	3,689	6,621	11,461
Specific Power	$SP/\frac{1}{SP}$	.089/11.2	.092/10.9	.123/8.1	.118/8.5	.134/7.5	.113/8.8
Transport Fraction	TF	.420	.533	.341	.368	.376	.426
Transport Efficiency	TE	4.72	5.79	2.77	3.12	2.81	3.78

TABLE C-6 (Con't)

SHIP			C-10/80/R	H-11/80/R	C-15/30/50	C-15/60/50	C-15/120/50	C-15/240/50
W100		(MT)	299.4	243.9	53.9	105.3	208.3	318
	\$1	(K\$)	10274	8770	2735	4586	7765	10764
Pi		(MHD)	44610	44610	12600	27300	62000	101000
	\$2	(K\$)	10603	10603	3818	7130	13834	20520
W300		(MT)	26.0	22.8	8.6	16.1	22.9	33.1
	\$3	(K\$)	1963	1742	717	1269	1749	2446
W400		(MT)	53.9	50.3	11.4	43.1	59.3	67.8
	\$4	(K\$)	5842	5598	2240	5089	6197	6731
W500-567		(MT)	130.1	89.4	17.2	45.3	95.5	167.4
	\$5	(K\$)	19191	14311	3944	8410	15069	23372
W567		(MT)	229	146.4	34.9	83.1	175.7	342.9
	\$567	(K\$)	23872	16825	5483	10805	19405	32734
W600		(MT)	92.5	69.1	18.3	38.6	74.2	125.1
	\$6	(K\$)	4228	3364	1187	2131	3557	5358
W700		(MT)	15.9	15.9	9.5	12.4	22.0	75.6
	\$7	(K\$)	289	289	174	226	398	1347
	Σ \$1-7	(K\$)	76262	61502	20298	39646	67974	103272
Design & Eng.	\$8	(K\$)	114931	90734	26833	56002	101280	160379
Const. Serv.	\$9	(K\$)	20442	17066	6733	11807	18561	26363
Wm		(MT)	122.2	94.9	26.9	60.0	114.8	205
	\$M	(K\$)	13198	10249	2905	6480	12398	22140
Total Const. Cost		(K\$)	224833	179551	56769	113935	200213	312154
15% Profit		(K\$)	33725	26933	8515	17090	30032	46823
	PRICE	(K\$)	258,558	206,484	65,284	131,025	230,245	358,977
HANDE NAME			NONE (21)	NONE (21)	UNK (10)	UNK (10)	UNK (10)	UNK (10)

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